A&A 477, 193–202 (2008)
DOI: 10.1051/0004-6361:20066086

Astronomy & Astrophysics

Extended shells around B[e] stars

Implications for B[e] star evolution

A. P. Marston[1] and B. McCollum[2]

[1] ESA/ESAC, Villafranca del Castillo, 28080 Madrid, Spain
e-mail: tmarston@sciops.esa.int
[2] Spitzer Science Center, IPAC, Caltech, Pasadena, CA 91125, USA
e-mail: mccollum@ipac.caltech.edu

Received 21 July 2006 / Accepted 15 October 2007

ABSTRACT

Aims. The position of B[e] stars in the upper left part of the Hertzsprung-Russell diagram creates a quandary. Are these stars young stars evolving onto the main sequence or old stars that are evolving off of it? Spectral characteristics suggest that B[e] stars can be placed into five subclasses and are not a homogeneous set. Such sub-classification is believed to coincide with varying origins and different evolutions. However, the evolutionary connection of B[e] stars – and notably sgB[e] – to other stars is unclear, particularly to evolved massive stars. We attempt to provide insight into the evolutionary past of B[e] stars.
Methods. We performed an Hα narrow-band CCD imaging survey of B[e] stars, in the northern hemisphere. Prior to the current work, no emission-line survey of B[e] stars had yet been made, while only two B[e] stars appeared to have a shell nebula as seen in the Digital Sky Survey. Of nebulae around B[e] stars, only the ring nebula around MWC 137 has been previously observed extensively.
Results. In this presentation we report the findings from our narrow-band optical imaging survey of the environments of 25 B[e] stars. Of the objects surveyed, 7 show bipolar or uni- polar structures up to 15′ across; 5 show faint, large, or filamentary shells; and 2 are compact planetary nebula-type systems. The most spectacular system observed is a large bipolar structure associated with MWC 314.
Conclusions. The possible links between B[e] stars and other evolved stars, implied by our observations, are investigated.

Key words. stars: emission-line, Be – stars: circumstellar material – stars: evolution

1. Introduction

The short lifetimes, large mass range and scarcity of very massive stars makes understanding the full range of their rapid evolutionary change more challenging than for lower mass stars. For stars above 40 $M_{\odot}$ there is no great consensus as to stellar evolutionary path. The uncertainties associated with the effects of rapid rotation and chemical abundances suggest a range of possible evolutionary tracks even for stars of similar initial masses (Meynet & Maeder 2003). However, it is widely believed that a short (10^4–10^5 years) but violent Luminous Blue Variable (LBV) phase, with possibly more than one eruption, occurs between an O and Wolf-Rayet (WR) phase of a star (Langer et al. 1998; de Koter 1993). For this to occur, a massive star evolving redward across the Hertzsprung-Russell (HR) diagram, following a few million years of life as a main sequence O star, hits an instability strip well before becoming a red supergiant (RSG). Following large-scale mass-loss, involving one or more eruptions that form a surrounding nebula, high mass stars are expected to evolve back towards the blueward side of the HR diagram and become a WR star.

B[e] supergiants ("sgB[e]") are found in a similar region of the HR diagram to WR and LBVs. No predictive link has been made between these three transitional star types in most models (e.g., Maeder & Meynet 2004). However, some models suggest an evolutionary sequence that include one or more B[e] phases in the evolution of stars with initial masses >30 $M_{\odot}$ (Stothers & Chin 1996; SC). In fact, SC indicate the possibility of H-rich and H-poor B[e] stars occurring before and after LBV and RSG phases of an evolving massive star. The existence of substantial spectral variability and equatorial outflows suggests a possible link between LBV and sgB[e] stars (Morris et al. 1997).

However, the B[e] phenomenon does not only exist in supergiant stars but also pre-main sequence (or "HAeB[e] stars"), compact planetary nebulae with type B[e] central stars ("cPNB[e]"), symbiotic B[e] (or "SymB[e]") stars or are unclassified B[e] stars (Lamers et al. 1998). Lamers et al. (1998) categorized 17 of their examined B[e] as supergiants, 9 as HAeB[e], 12 as cPNB[e] and 28 as "unclassified" B[e] stars. With many of the unclassified objects having properties that allow them to be placed into more than one mutually exclusive category. While for other "unclassified" B[e] stars the existing diagnostic data are insufficient for clear sorting. Thus the evolutionary status of a significant fraction of B[e] stars is unknown, while the physical nature of a number of others remain a matter of some conjecture.

Our study therefore includes B[e]-type stars of various classifications, to also potentially provide information on the environment of the different B[e] classes, help to better classify B[e] stars (notably some of the unclassified B[e] stars) as well as attempting to find possible evolutionary links to other massive stars.

2. The large-scale circumstellar environment of B[e] stars

It is widely believed that the emission-lines seen in the spectra of B[e] stars emanate from a circumstellar disk-like structure where

Article published by EDP Sciences and available at http://www.aanda.org or http://dx.doi.org/10.1051/0004-6361:20066086

emission-lines (including forbidden lines) are formed. Such a disk is possibly created via a two component wind (Zickgraf et al. 1985). Although the existence of disks around B[e] stars is occasionally debated (Owocki et al. 1996). High-resolution line profile observations by Zickgraf (2003) clearly indicate the presence of a disk-like structure around the equatorial regions of B[e] stars. It is also clear from polarization measurements that the immediate circumstellar environments are characterized by non-spherical distributions of particles (Oudmaijer & Drew 1999; Barbier & Swings 1982).

The large-scale environment of B[e] stars, out to several parsecs, provides us with the opportunity of looking at the past long-term evolutionary effect of the stars on surrounding interstellar medium, as well as any influence circumstellar disks may have had in this interaction. Studies of materials in the environments of LBV and WR stars have provided vital clues as to the evolution of individual stars (e.g., Waters et al. 1997; Marston 1995; Gruendl et al. 2000). The environment surrounding evolved massive stars has the potential to provide

1. mass-loss history;
2. timescales of intermediate phases;
3. geometry of mass-loss;
4. chemistry of the stars at the time of nebula formation.

Such properties obviously have a strong bearing on the nature of B[e] stars and it is relatively surprising to find that little information exists in the literature on the nature of extended (>1′) circumstellar emission around galactic B[e] stars. The most extensive study was done by Esteban & Fernandez (1998) who imaged and spectrally analyzed the ring nebula around the B[e] supergiant star MWC 137. MWC 137 is surrounded by an inhomogeneous elliptical ring nebula of $\sim 2 \times 1.5$ pc. The morphology and size of this ring is similar to that of LBVs. The narrow, and sometimes split, emission-lines observed suggest the ring is expanding at 10−15 km s^{-1} giving a dynamical age of 10^5 years. Most puzzling is the lack of enhanced N and/or He abundances as has been observed in most LBV and WR nebulae, suggesting the ring is not composed of ejecta from the surface of an evolved star but rather comes from a relatively chemically unevolved period or is composed of swept-up residual circumstellar matter from the star's formation period.

The evolutionary clues that might be provided by the circumstellar material associated with B[e] stars has prompted Schulte-Ladbeck (1998) to urge for a survey of B[e] star environments. This paper is a first attempt to address this need.

In order to investigate the typical environments of B[e] stars we have undertaken an imaging study of all known or suspected B[e] available in the northern hemisphere. Several of these objects have had one or more other classifications (such as Luminous Blue Variable, LBV, candidate). Information on the B[e] stars investigated is provided in Tables 1 and 2 where we list the properties of target objects, with and without observed extended emission respectively.

3. Observations

Given the possibility of finding clues to the evolution of B[e] stars from their circumstellar environments, we have undertaken a program to find large-scale structures around B[e] stars regardless of subtype (see Lamers et al. 1998). Most of the B[e] stars in our sample remain "unclassified" B[e] stars with unknown evolutionary status.

Our observations were made with the 60-inch telescope on Mt. Palomar over the course of several observing runs in 2001 and 2002 under varying weather conditions. We used the observatory's CCD13 chip (2048^2 pixels) together with a narrow band Hα filter (λ = 6564.8 Å, $\Delta\lambda$ = 20 Å). Pixel size was 0.″367 on a side providing a field of view of 12.′5 on a side and exposure times were typically 15−30 min, providing a "roughly" magnitude limited survey.

A total of 25 B[e] star environments were imaged. In cases where extended emission was apparent, mosaicing of fields was done over an enlarged area.

4. The B[e] sample

In Tables 1 and 2 we provide a summary of information and results for our sample set of B[e] stars. Approximately 50% show some kind of evidence for extended structures that are several arc minutes across and are included in Table 1. Objects in Table 2 show no extended structures. All objects in Table 2 were detected in at least one bandpass by IRAS, and all have been noted in the literature as variable except for SS73 170. Spectral types and *V* magnitudes in each of the tables are from SIMBAD and classifications are taken from Thé et al. (1994) unless otherwise noted. "Uncertain" classifications indicate that Thé et al. were uncertain whether object is a HAeBe star, or "extreme emission line object" (EELO) of uncertain category. The B[e] star classification comes from Lamers et al. (1998); "unclassified" in this column means that Lamers et al. were not able to arrive at a categorization, while "NA" indicates that the object was not included in their study.

5. Results for individual stars

In the following subsections we discuss the different structural phenomena seen and the associated stars.

5.1. Nebulae around two supergiants

The most spectacular environment is that of MWC 314 (see Fig. 1). MWC 314 is a supergiant B[e] star that has been identified as one of the most luminous stars in the galaxy, with Miroshnichenko (1996) putting its luminosity at Log $L_{\rm Bol}$ = 6.1 ± 0.3 $L_\odot$. Our image shows it has a very large bipolar nebula structure around it that is approximately 15′ in total length. For a distance of 3 kpc (Miroshnichenko et al. 1998) this makes the bipolar structure 13.5 pc from end to end.

It is difficult to imagine such a large-scale structure being formed around the star in a short period of time. If the expansion speed of the bipolar was as much as 50 km s^{-1} then the bipolar structure would take more than 10^5 years to form. This expansion speed is at the moderate to high end for LBV nebular expansion (Nota et al. 1995), although Weis (2003) notes several younger LBV nebulae as having expansion velocities that are twice as great. A more accurate measure of the dynamical timescale for formation will require follow-up measurements of the expansion of the observed bipolar feature. What is clear is that the observed bipolar structure is 5 times larger than typical LBV nebulae (although a unipolar structure extends for a similar distance on one side of P Cygni, see Meaburn et al. 2004).

The ring nebula (S266) around MWC 137 has been studied by Esteban & Fernandez (1998), as noted in the introduction, who indicate that the stellar and nebular spectra are indicative of the star being a B[e] supergiant. Our deeper emission-line image

Table 1. B[e] stars observed to have associated extended Hα emission.

ID	Sp. type	V Magnitude	Other classifications	Hα Structure (our results)	Lamers et al.'s classification	Comments
MWC 314	B	9.9	sgB[e] & LBV[1]; uncertain	double lobe	unclassified	No binarity detected[2]
MWC 137	Be	11.2	sgB[e][3]; HAeBe	bipolar with ring	NA	Misclassified as PN[4]; optical nebulosity; variable unresolved radio source; no binarity detected[5]; possible extended dust[6]
MWC 419	Be	10.6	HAeBe; O9III[7]	multiple unipolar lobes	NA	Associated optical nebulosity[8]
MWC 349A	Be	13.2	PN[9]; pre-MS[10]; uncertain; not pre-MS[13]	shell	uncl./sg?B[e]	Near-IR edge-on disk resolved[11]; possible periodic variable[12]; radio data suggest bipolar outflow[10];masing star[14]
MWC 84	Be	11.7	uncertain; sgB[e][15]	partial arc	uncl./cPNB[e]?	High-mass X-ray binary[16]
MWC 342	Be	10.6	HAeBe; not pre-MS[13]	shell	unclassified	Possible binary, "evolved", not symbiotic or pre-MS[17]
MWC 657	Be	12.6(M_B)	uncertain	shell	NA	Binary[18]
Hen 2-461	Bpe	14.7	uncertain	shell	unclassified	"Nebula of unknown nature" (not a PN)[19]
MWC 1080	B0	11.6	HAeBe[8]	bipolar	HAeBe	Short-period (2.89d) ecl. binary[20]; dusty disk[21]
MWC 361	B2/3Ve[22]	9.1	HAeBe	bipolar	HAeBe	Long-period binary[23]; associated with NGC 7023; shell star[24]
MWC 922	Be	13.9	Not HAeBe; Pre-MS[25]; possible post-AGB[26]	jet-like lobe	unclassified	

[1] Miroshnichenko (1996), [2] Corporon & Lagrange (1999), [3] Esteban & Fernandez (1998), [4] Zijlstra et al. (1990), [5] Baines et al. (2006), [6] Mannings (1995), [7] Zorec (1998), [8] Herbig (1960), [9] Ciatti et al. (1974), [10] Rodriguez & Bastian (1994), [11] Danchi et al. (2001) [12] Jorgenson et al. (2000), [13] Vinković & Jurkić (2007), [14] Thum et al. (1994), [15] Miroshnichenko et al. (1998), [16] Hjellming et al. (1998), [17] Miroshnichenko & Corporon (1999), [18] Miroshnichenko et al. (2000), [19] Acker et al. (1987), [20] Shevchenko et al. (1994), [21] Fuente et al. (2002), [22] van den Ancker (1998), [23] Pirzkal et al. (1997), [24] Mendoza (1958), [25] Likkel et al. (1991), [26] Pereira et al. (2003).

clearly shows the ring nebula, but also shows the existence of a diffuse bipolar structure that appears to "thread" the ring nebula (see Fig. 2). Fan-like structures are noted to the south-east and north-west of the star which are perpendicular to a disk of continuum 1.3 mm emission observed by Fuente et al. (1998a – also see Henning et al. 1998), which presumably is associated with cold dust emission. The diffuse Hα emission appears associated with a large-scale bipolar outflow perpendicular to a cold, dense disk.

Esteban & Fernandez (1998) indicate that the ring nebula around MWC 137 expands at a relatively slow speed ($10-15$ km s^{-1}) implying the ring nebula is again around 10^5 years old.

5.2. Single-lobed structures

Unipolar structures are observed around three of the stars in our sample (see Fig. 3). MWC 419 (V594 Cas; a HAeB[e] star) appears to exhibit two lobes on the same southern side of the star. The outer, faintest, lobe is 4′ long. The "lobe inside a lobe" appearance suggests multiple episodes of mass outflow. It is interesting to note that multiple episodes of mass-loss are believed to be required for stars proceeding from a LBV to a WR phase and have been observed around η Car and P Cygni (e.g., Walborn 1976; Smith & Hartigan 2006). Obscuration likely prevents the northern lobe(s) from being viewed.

MWC 922 and MWC 819 are two "unclassified" B[e] stars that show lobes that are a few arc minutes long, with MWC 922 showing an almost "jet-like" appearance to the south east of the star. This star has strong crystalline silicate dust features with both O-rich and C-rich features observed in the mid-infrared (Voors 1999). Voors argues that MWC 922 has a long-lived dust disk around it containing evolved materials. Clearly a jet-like outflow can be constrained by just such a massive disk

5.3. Faint shells and arcs

MWC 349A is an uncl/sg?B[e] star. It is the only known star to show masing emission-lines (Thum et al. 1994). An apparent thin shell of approximately 2.′5 diameter exists around MWC 349A to the north (see Fig. 4). Faint shells were also seen around the B[e] stars MWC 84 (CI Cam, a sgB[e] X-ray binary), MWC 342, MWC 657 and He 2-461 (see Fig. 4). It is interesting to note that 3 of these 4 stars have been identified as B[e] stars with warm dust (B[e]WD – Miroshnichenko 2005) while the fourth, He 2-461 is associated with an IRAS source with a strong 12 and 25 micron flux, also indicative of warm dust. Both MWC349A (a sgB[e] star) and He 2-461 have a ratio of 12 to 25 microns flux similar to the other three objects. This would indicate a connection between warm circumstellar dust and the presence of more distant shells.

Table 2. B[e] star targets which were not observed to have extended Hα emission.

ID	Sp. type	V Magnitude	Other classifications	Lamers et al.'s classification	Comments
V 1012 Ori	none	12.1	HAeBe	NA	Algol variable[1]; mm obs. found no cold dust[2]
MWC 17	Be	12.2	EELO[3]; A/B[4] young object[5] O9I with envelope[6]	NA	Symbiotic binary
MWC 142	Bpshe	8.1	EELO; Evolved object[7] HAeBe[9]; not pre-MS[10]	unclassified	No cold dust at 20μ[8]
MWC 162	Bpe	11.1	EELO; Proto-PN[11] HAeBe[13]	unclassified	Possible symbiotic binary[12]
MWC 300	Bpe	10.5	HAeBe; B1Ia[14]	unclassified	
MWC 623	Be	10.5	uncertain	NA	Early B + early K binary with strong Li emission from K[15]
SS73 170	F6e	14.3	uncertain	unclassified	2μ excess, unremarkable Be-type spectrum[16]
MWC 158	B9e	6.58	EELO; B6III[17]; B5III[18] pre-MS Be star[21]	NA	Spectroscopic shell[19,20]
MWC 645	Be	12.5	uncertain	unclassified	Spectroscopic shell[22]
AS 321	A3V	11.0	uncertain possible post-AGB[24] not a PN[25]	NA	Not a binary[23]
MWC 1055	Be	12.4	uncertain B[e]	unclassified	

[1] Miroshnichenko et al. (1999), [2] Henning et al. (1994), [3] Thé et al. (1994), [4] Jaschek & Andrillat (1999), [5] Muratorio et al. (2006), [6] Leibowitz (1977), [7] Monnier et al. (2006), [8] Simon & Dyck (1977), [9] Grady et al. (1993), [10] Vinković & Jurkić (2007), [11] Andrillat & Swings (1976), [12] García-Lario et al. (1990), [13] Valenti et al. (2000), [14] Wolf & Stahl (1985), [15] Zickgraf & Stahl (1989), [16] Allen & Swings (1976), [17] Cidale et al. (2000), [18] Jaschek & Andrillat (1999), [19] Doazan (1965), [20] Hutsemekers (1985), [21] Lamers et al. (1998), [22] Jaschek et al. (1996), [23] Corporon & Lagrange, (1999), [24] Parthasarathy et al. (2000), [25] Umana et al. (2004).

However, the association of of these shells with the central stars is more tenuous than for the polar lobe cases. There is no evidence to clearly indicate that these features are associated with stellar ejecta. Indeed it is quite possible that these are simply illuminated local interstellar materials, although the presence of MWC 349A at the centre of a semi-circular shell clearly suggests the influence of the star on the interstellar medium.

5.4. Diffuse bipolar structures

Two large bipolar features are noted around the HAeB[e] stars MWC 1080 and HD 200775 (with nebula NGC 7023). These are shown in Fig. 5. Although the northern lobe of MWC1080 appears to be partially missing or obscured. The features can also be seen in Digital Sky Survey images so are quite bright. These lobes are more diffuse than the large bipolar around MWC 314. This suggests they are not currently being formed by the interaction of stellar winds with the surroundings, but mark a ragged photionized boundary of regions previously excavated by the outflows from the central stars. Indeed, comparison of the structures around MWC 1080 with the sub-mm observations of Fuente et al. (1998a) and Henning et al. (1998) suggests that the large outer lobe marks the edge of a region of cool, dusty materials, as seen in their maps at 1.3 mm.

It has been shown that MWC 1080 is a binary with a separation of 0.″76 (Leinert et al. 1997) as well as having an eclipsing binary companion with a period of 2.89 days (Shevchenko et al. 1994). It also has a dusty disk that is along the south-east to north-west axis that is perpendicular to the direction of the bipolar lobes seen in Fig. 5 (Fuente et al. 2003).

HD 200775 is also in a binary system with a 3.68 year period (Pogodin et al. 2004). The surrounding reflection nebula is NGC7023 (see Fig. 5). The molecular CO maps of Fuente et al. (1998b) show how the bipolar cavity sits within a molecular shell of gas. This clearly suggests diffuse ionized gas on the interior of a pre-defined bipolar structure is being seen in our observations. Fuente et al. (2002) suggest this is associated with the protostar to type I HAeBe early stage of intermediate mass star evolution.

5.5. Objects with no extended emission

The following B[e] stars had no visible extended emission associated with them. V 1012 Ori (more probably a HAeBe star), MWC 17, HD 45677, MWC 162, MWC 300, MWC 623, SS 73-170, MWC 158, MWC 645, MWC 1055, and AS 321 (see Fig. 6). Most of these are unclassified B[e] stars.

However, MWC 300 is a supergiant, and the lack of obvious circumstellar nebula materials around the star is, at first, quite puzzling if supergiant B[e] stars are believed to be evolved objects which have lost significant mass. However, Miroshnichenko et al. (2004) indicate quite strong interstellar extinction along the line of sight, and their distance estimate of 1.8 kpc makes the star less luminous than previously believed. The lack of any obvious ionized shells may therefore not be so strange. It is also in a close binary system (Takami et al. 2003) which may have lead to a different evolution for this supergiant B[e] star as compared to the other supergiants in our sample.

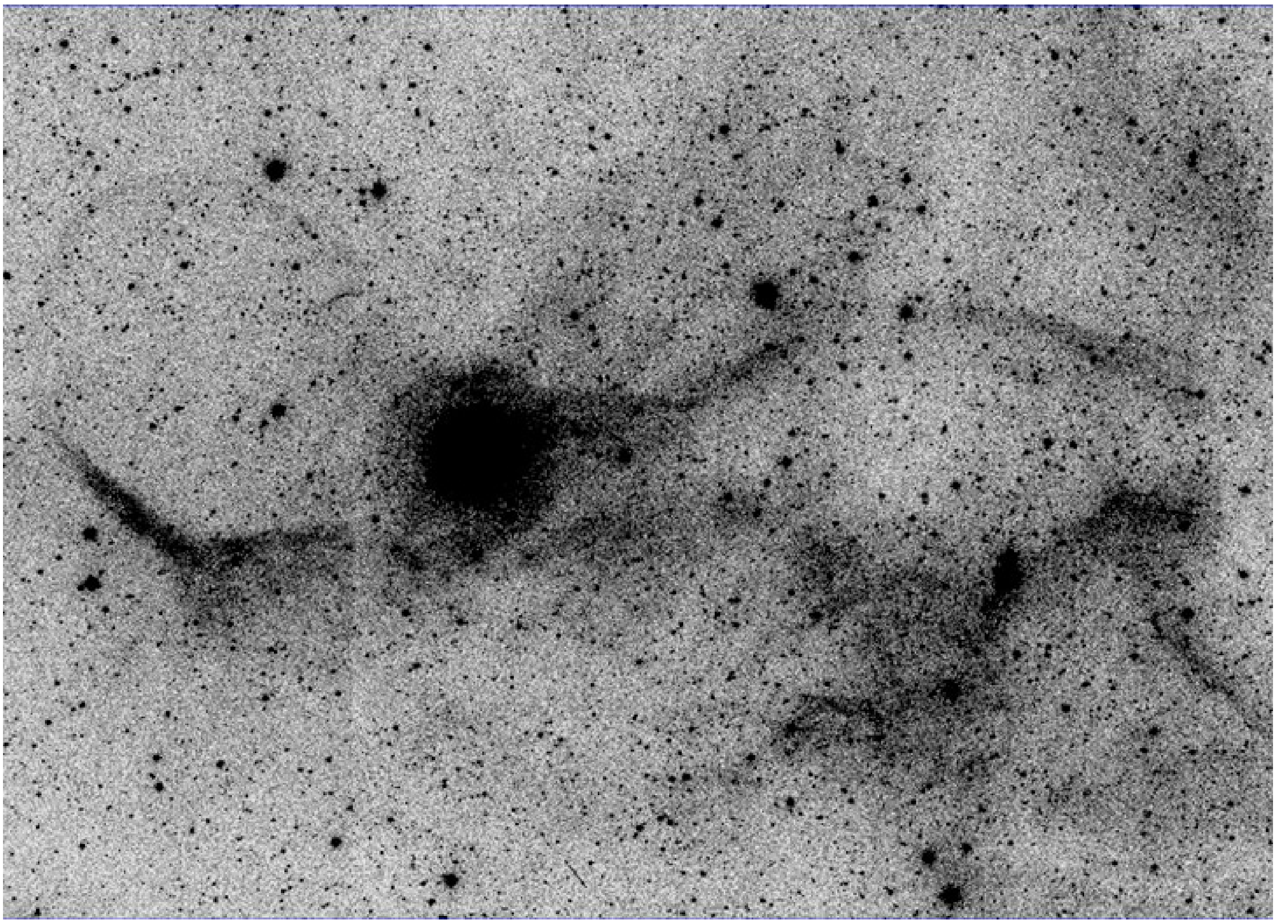

Fig. 1. Narrow band Hα image of the environments of MWC 314 showing the large east-west bipolar feature around the star. The figure is 12.′5 vertically. For all figures, north is up and east to the left.

5.6. Compact planetary nebulae

Two further B[e] stars in our survey were previously identified as compact planetary nebulae. No further extended emission was seen associated with either M 2-56 or He 3-1475.

6. Discussion

6.1. Survey limitations

The results of our survey are tabulated in Tables 1 and 2, which contain information on the stars with detected extended emission and those where no extended emission was found respectively.

We briefly consider whether there is reason to suspect that many of the negative results with respect to observing extended emission were negative simply because our survey was fairly magnitude-limited. This cannot be assessed with great precision because the absolute magnitudes and distances of most of our targets are not well known. We can, nevertheless, indirectly make a tentative assessment of the completeness of our survey.

We found extended emission in four out of five known or candidate sgB[e] stars surveyed. The only sgB[e] candidate for which extended emission was not seen is MWC 300, which, as discussed previously, may not be a supergiant. Even assuming that MWC 300 is a supergiant, we do not believe it is likely that it has comparable extended emission to that of the other sgB[e] stars which we failed to image because of our exposure time limitation. The four sgB[e] stars for which we found extended emission have *V* magnitudes ranging from 9.9 to 13.2, with a mean *V* magnitude of 11.5. MWC 300 has a *V* magnitude of 10.5, which is actually brighter than three of our four "positives". We can conclude that the apparent absence of extended Hα emission near MWC 300 in our images is probably real. Since photoionized gas Hα emission is dependent on the rate of recombination of hydrogen, it is dependent on the square of the density of ions/electron as well as the rate of photoionization. Any circumstellar material from MWC 300 is therefore likely to be more diffuse than for that of the other sgB[e] stars.

Lamers et al. (1998) suggest that many of the unclB[e] stars would in fact be classed as sgB[e] stars if accurate distance and luminosity information were available. Our sample included eight of Lamers et al.'s unclB[e] stars, not counting a few which Lamers et al. considered to be "unclassified" but which we and other authors have accepted as sgB[e] stars. Among those unclB[e] stars, we found three with extended emission and five without. While admittedly these are small number statistics, the fact that we found prominent extended emission around four of five known sgB[e] stars but only 3/8 of unclB[e] stars suggests that a high fraction of unclB[e] stars are not sgB[e] stars, although certainly a small fraction could be.

The mean *V* magnitude of Lamers' unclB[e] stars in our sample is 11.96, covering a range from 14.3 to 8.0. As stated above, the mean *V* magnitude for the sgB[e] stars we observed is 11.5, ranging from 13.2 to 9.9. Given the variability of weather conditions during our observing (clear to thin clouds), we do not think that a mean difference of half a magnitude is strongly

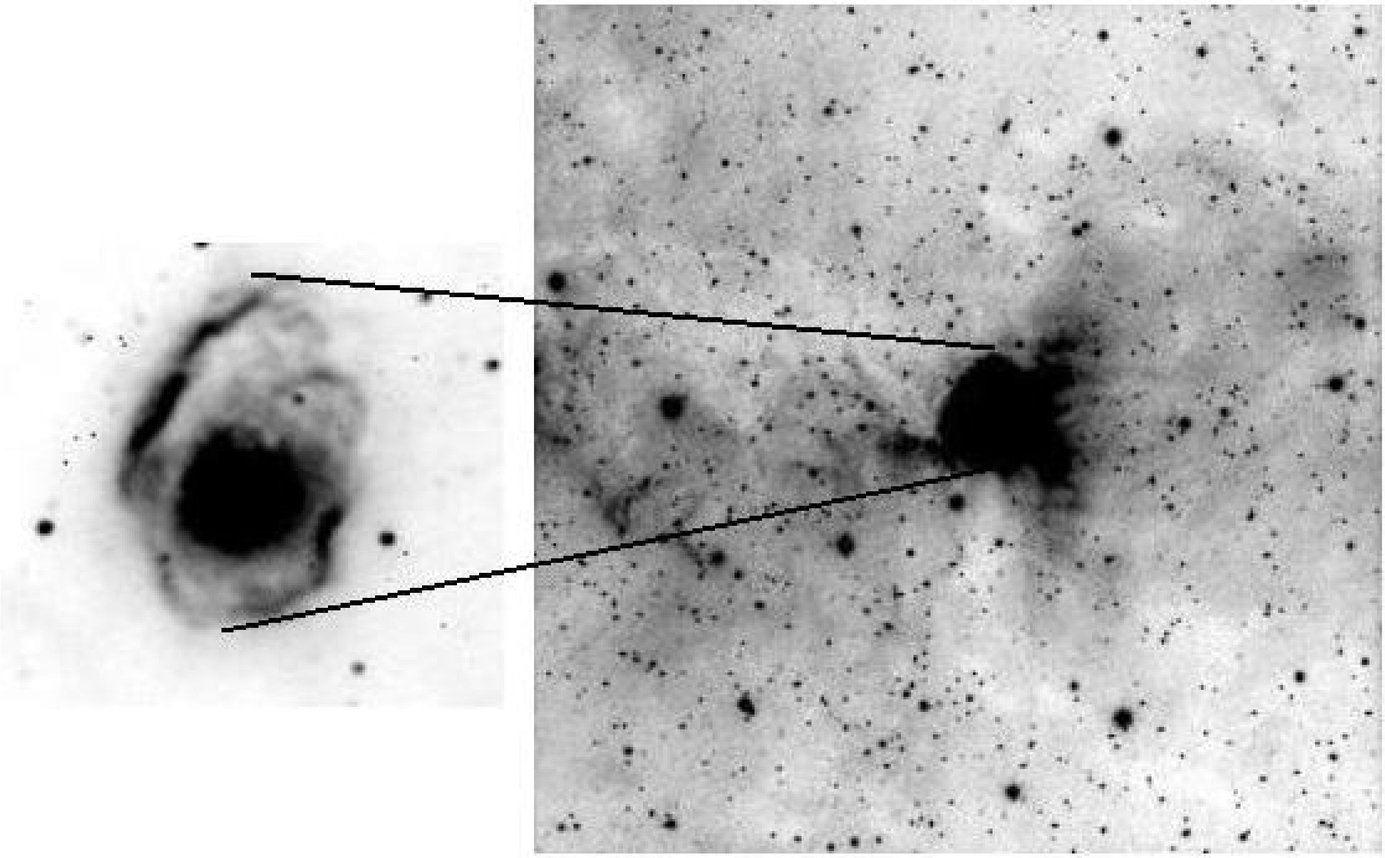

Fig. 2. Narrow band Hα image of the environments of MWC 137 with ring nebula shown as inset. Large-scale image is 12.′5 across. The central ring has a major axis diameter of 70″.

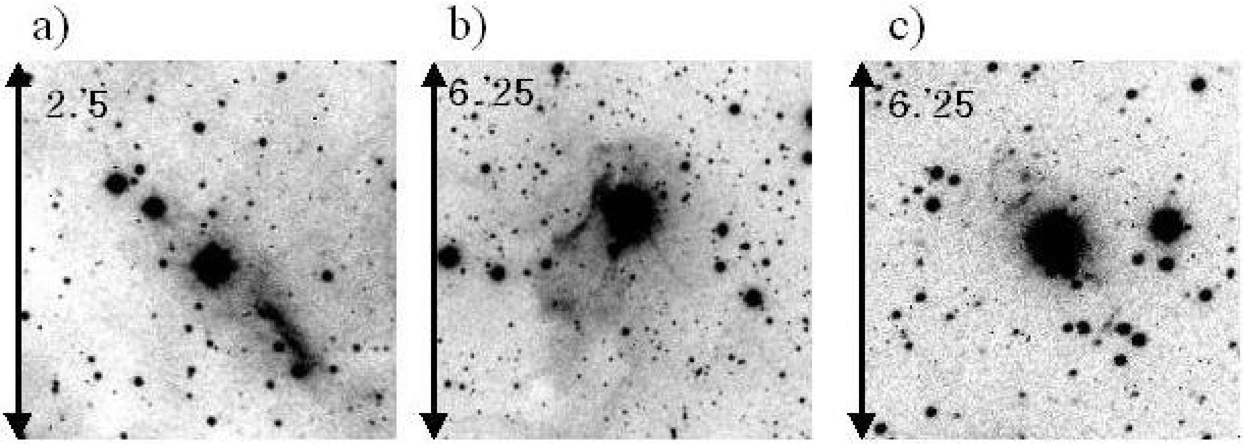

Fig. 3. Narrow band Hα image of the environments of **a)** MWC 922, **b)** MWC 419 and **c)** MWC 819 showing lobes on one side of each of the stars only.

indicative of a magnitude bias in our results for sgB[e] and unclB[e] objects.

6.2. sgB[e] stars and massive star evolution

Considering the masses found for galactic WR stars at the end of their evolution ($\approx$20 $M_{\odot}$, Massey 1981 – although a large range is found), considerable mass-loss is required between the main sequence O star phase and WR. Since 2−3 $M_{\odot}$ are believed to be lost in a single LBV eruption (e.g., Humphreys 1989), several eruptions may be needed prior to a WR phase. Alternatively, other transitional, high mass-loss phases may be involved in the evolution.

Some indications from both crystalline dust formation in LBV nebulae (Waters et al. 1997) and theory (SC) suggest a number of high mass stars may actually move into a RSG or YSG phase prior to becoming LBVs. Studies of stellar dynamical instabilities in the upper HR diagram by de Jager et al. (2001) indicate two regions of key instabilities, a "blue" and "yellow-red" region. Massive stars evolving blueward from a red hyper-/supergiant phase can evolve through these regions of instability. In particular, the atmospheres of blueward-evolving

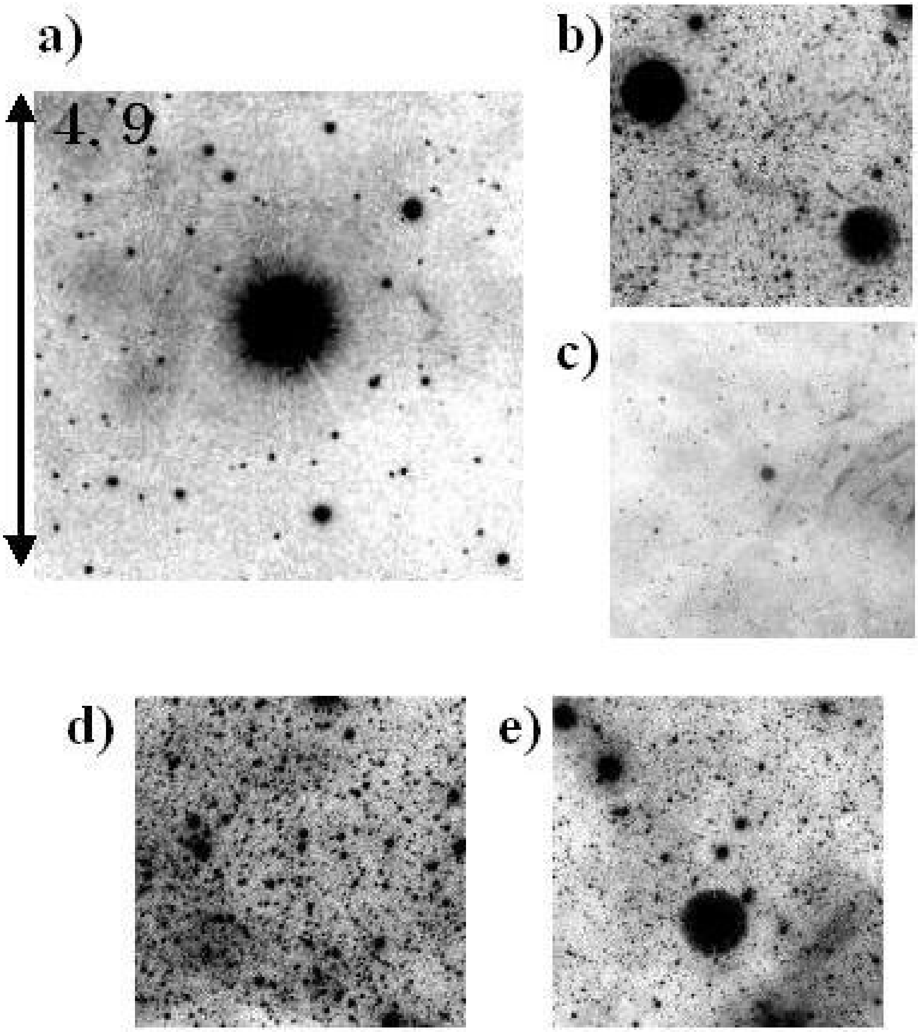

Fig. 4. Narrow band Hα image of the environments of **a)** MWC 349A, **b)** MWC 84 – bright star to bottom right, **c)** MWC 342, **d)** MWC657 and **e)** He 2-461, showing faint shells arc structures around the stars. All images are 12$'\!.$5 on a side except for MWC 349A.

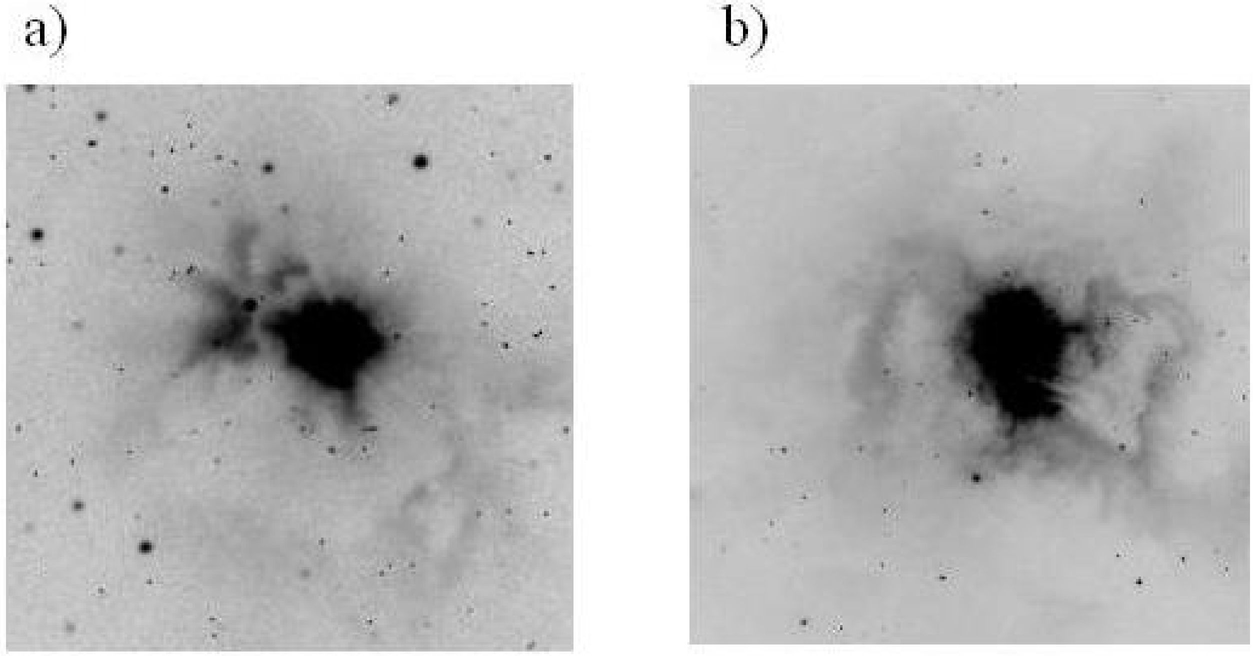

Fig. 5. Narrow band Hα image of the environments of **a)** MWC 1080 and **b)** HD 200775 showing large, diffuse lobe structures.

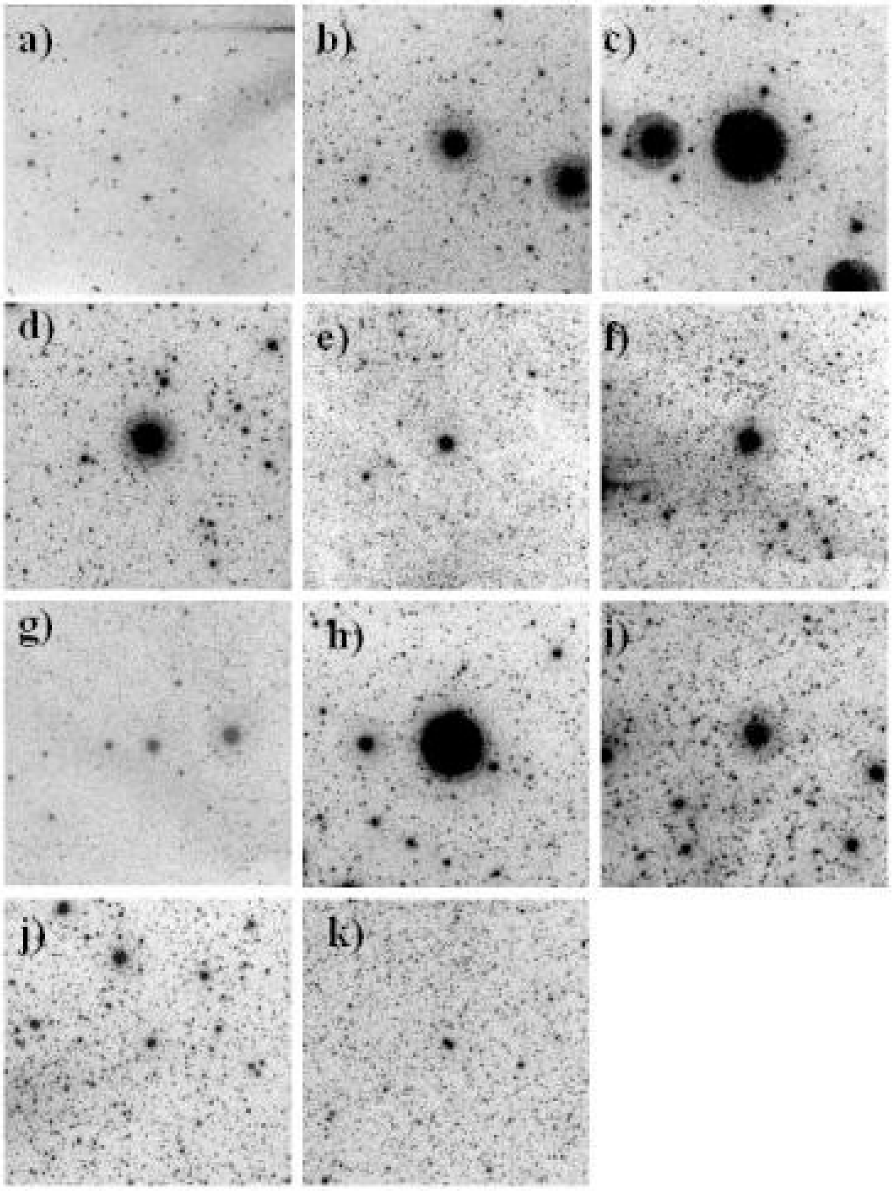

Fig. 6. Narrow band Hα image of the B[e] stars showing no evidence for extended circumstellar structures, **a)** V 1012 Ori, **b)** MWC 17, **c)** HD 45677, **d)** MWC 162, **e)** MWC 300, **f)** MWC 623, **g)** SS 73-170, **h)** MWC 158, **i)** MWC 645, **j)** MWC 1055, and **k)** AS 321. All images are 12.′5 on a side and have the star centrally positioned in the frame.

supergiants become unstable at around 8000 K at which point a LBV can be formed from a post-RSG star.

SC go further, indicating the following possible evolutionary scenarios for massive stars.

For stars with initial masses >60 $M_{\odot}$: $O \rightarrow Of \rightarrow H-rich\,WN \rightarrow H-rich\,B[e] \rightarrow YSG \rightarrow Yellow\,LBV \rightarrow H-poor\,WN(or\ H-poor\,B[e]) \rightarrow Blue\,LBV \rightarrow H-free\,WN \rightarrow WC \rightarrow SN.$

For stars with initial masses of 30–60 $M_{\odot}$: $O \rightarrow Of \rightarrow H-rich\,B[e] \rightarrow RSG \rightarrow Red\,LBV \rightarrow H-poor\,WN \rightarrow H-poor\,B[e] \rightarrow Blue\,LBV \rightarrow H-free\,WN \rightarrow WC \rightarrow SN.$

With either form of the SC evolution, B[e] stars are expected to be involved. The fact that so few sgB[e] stars are known puts them in a class similar to that of LBVs. The lack of numbers can therefore be interpreted as being due to a relatively short lifetime for the sgB[e] phase.

Extended shell and bipolar structures around 4 out of 5 of the sgB[e] stars observed might suggest an evolutionary connection to other evolved massive stars with extended nebulae, such as LBVs and WRs. One possibility is that sgB[e] stars such as MWC 314 and MWC 137 have evolved from a LBV stage and are moving blueward in the HR diagram, as is illustrated in both SC evolutionary sequences. The large bipolar structure around MWC 314 is morphologically similar to that around η Car but much larger. Miroshnichenko et al. (1998) indicate N/O overabundances in the spectrum of MWC 314 which suggests the star is evolved in a similar way to LBVs. Indeed they suggest it is an LBV candidate, despite stellar spectra showing double-peaked line shapes and no blue-shifted absorption components, which characterize several sgB[e] spectra.

However, in contrast, the age of the large bipolar structure around MWC 314 is approximately ten times that of other LBV nebulae (Nota 1995) and its timescale for formation is at the upper end of the time period for the LBV phase of massive stars of 10^4 to 10^5 years (Bohannan 1997). We also currently have no evidence that the bipolar structure around MWC 314 contains processed materials or was formulated in a similar way or at a similar phase to LBV nebulae. There is therefore no clear evidence of a connection between the nebula around MWC 314 and LBV nebulae.

For MWC 137, the ring nebula is composed of unprocessed materials, suggesting swept up interstellar matter (e.g., part of a disk created in the formation stage of the star) or expelled material from the surface of the star in an early phase of its evolution, rather than in a LBV ejection. Indeed Esteban & Fernandez (1998) suggest ejection from the surface of an unevolved star, as a source for the shell. Another possibility is that, in some circumstances, sgB[e] stars are formed in an alternative intermediate phase en route between being O and Wolf-Rayet stars, as suggested by Zickgraf (1992). If this were the case for MWC 137, then it may not yet have gone through a post main sequence evolutionary phase of ejection with associated higher abundances of heavier elements such as nitrogen.

With no evidence of nebular abundance enhancements associated with sgB[e] nebulae, we have no proof of connection between LBV and sgB[e] nebulae and the possibility of evolution from LBV to H-poor sgB[e]. More likely appears to be either swept up local interstellar medium or an ejection during an early H-rich sgB[e] phase when stellar surface abundances could be expected to be similar to those of the surroundings. An equatorial disk, believed to exist around B[e] stars, would restrict the wind outflow from MWC 314 in the former case, forming a bipolar structure.

7. Conclusions

Our narrow-band imaging survey of the environments of 25 galactic B[e] stars has shown that approximately half have associated extended structures. In the case of known supergiant B[e] stars, 4 out 5 stars show evidence of extended emission, with MWC 300 being the only exception.

A total of 7 out of 25 galactic B[e] stars surveyed showed unipolar/bipolar structures, 5 showed faint shells and 2 were known compact planetary nebulae that showed no highly extended materials. Large-scale structures are therefore seen around a similar fraction of B[e] stars as have previously been seen around WR stars (approx. 50%). The most spectacular structure is seen around MWC 314, a sgB[e] star, which has extended bipolar lobes that are >13 pc end to end, and would likely have taken more than 10^5 years to form. The timescale for the formation of the ring nebula S266 around MWC 137, another sgB[e], is also 10^5 years (Esteban & Fernandez 1998). Zickgraf (1992) suggests, from the statistics of B[e] supergiants in the Small Magellanic Cloud, that the B[e] phase lasts $\geq 10^5$ years. This figure is based on small number statistics and may not be appropriate for our own galaxy where the metallicity is significantly higher. It is also based on the observational lack of LBVs in the Small Magellanic Cloud and the assumption that the sgB[e] state must likely therefore be the intermediate state of a star going from O to WR. However, these all point to a timescale for sgB[e] phase of one to possibly a few times 10^5 years.

Several cases of nebular bipolarity are evident. Bipolarity is a feature of LBV nebulae and this might suggests morphological connection. But the large-scale features associated with MWC 314 suggest a greater nebula age than for LBV nebulae generally and as of yet there is no evidence of N and He abundance enhancements for B[e] nebulae, as is the case for LBV nebulae.

The existence of non-spherical flows lends credence to the idea that temporally stable disks exist around a large fraction of B[e] stars. These have lead to the formation of non-spherical flows over periods of at least 10^5 years.

For two of the systems, MWC 137 and MWC 419, there appears to be more than one episode of mass-loss evident. For MWC 137 an east-west bipolar fan structure is accompanied by a separate bright ring around the central star. While for MWC 419 a faint, more diffuse outer lobe to the south of the star appears to contain a second inner lobe suggesting more than one outflow or eruption has occurred in association with the central star.

Future studies of the observed shells can potentially provide information on the chemistry of the observed structures and indicate whether shell materials come from the surface of an evolved massive star (ejecta materials – as is typically the case for WR and LBV shells), or are composed of less evolved material, such as swept up local interstellar medium. Expansion velocity information can also provide better dynamical timescales for their formation.

Acknowledgements. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

References

Acker, A., Chopinet, M., Pottasch, S. R., & Stenholm, B. 1987, A&AS, 71, 163
Allen, D. A., & Swings, J. P. 1976, A&A, 47, 293
van den Ancker, M. E., de Winter, D., & Tjin a Djie, H. R. E. 1998, A&A, 330, 145
Andrillat, Y., & Swings, J. P. 1976, ApJ, 204, L123
Baines, D., Oudmaijer, R. D., Porter, J. M., & Pozzo, M. 2006, MNRAS, 367, 737
Barbier, R., & Swings, J. P. 1982, in Be stars, Proc. Symp., Munich, West Germany, April 6−10, 1981, A83-10301 01-90 (D. Reidel), 103
Bohannan, B. 1997, in Luminous Blue Variables: Massive Stars in Transition, ed. A. Nota, & H. J. G. L. M. Lamers, ASP Conf. Ser., 120, 3
Ciatti, F., D'Odorico, S., & Mammano, A. 1974, A&A, 34, 181
Cidale, L., Zorec, J., & Morrell, N. 2000, The Be Phenomenon in Early-Type Stars, IAU Colloq. ,175, ed. M. A. Smith, & H. F. Henrichs, ASP Conf. Proc., 214, 87
Corporon, P., & Lagrange, A.-M. 1999, A&AS, 136, 429
Danchi, W. C., Green, W. H., Hale, D. D. S., et al. 2001, ApJ, 555, 405
Doazan, V. 1965, A&A, 28, 1
Esteban, C., & Fernandez, M. 1998, MNRAS, 298, 185
Frémat, Y., Neiner, C., Hubert, A.-M., et al. 2006, A&A, 451, 1053
Fuente, A., Martín-Pintado, J., Bachiller, R., Neri, R., & Palla, F. 1998a, A&A, 334, 253
Fuente, A., Mart'in-Pintado, J., Rodr'iguez-Franco, A., & Moriarty-Schieven, G. D. 1998b, A&A, 339, 575
Fuente, A., Martín-Pintado, J., Bachiller, R., Rodríguez-Franco, A., & Palla, F. 2002, A&A, 387, 977
Fuente, A., Rodríguez-Franco, A., Testi, L., et al. 2003, ApJ, 598, L39
García-Lario, P., Manchado, A., Suso, S. R., Pottasch, S. R., & Olling, R. 1990, A&AS, 82, 497
Grady, C. A., Bjorkman, K. S., Shepherd, D., et al. 1993, ApJ, 415, 39L
Gruendl, R., Chu, Y.-H., Dunne, B. C., & Points, S. D. 2000, AJ, 120, 2670
Henning, Th., Launhardt, R., Steinacker, J., & Thamm, E. 1994, A&A, 291, 546
Henning, Th., Burkert, A., Launhardt, R., Leinert, Ch., & Stecklum, B. 1998, A&A, 336, 565
Herbig, G. H. 1960, ApJS, 4, 337
Hjellming, R. M., Mioduszewski, A. J., Ueda, Y., et al. 1998, IAU Circ., 6872
Humphreys, R. M. 1989, in Physics of luminous blue variables, Proceedings of the 113th IAU Colloq., Val Morin, Canada, Aug. 15−18, 1988, A90-33004 13-90 (Dordrecht and Boston, MA: Kluwer Academic Publishers), 3
Hutsemekers, D. 1985, A&AS, 60, 373
de Jager, C., Lobel, A., Nieuwenhuizen, H., & Stothers, R. 2001, MNRAS, 327, 452
Jaschek, C., & Andrillat, Y. 1999, A&AS, 136, 53
Jaschek, M., Andrillat, Y., & Jaschek, C. 1996, A&AS, 120, 99
Jorgenson, R. A., Kogan, L. R., & Strelnitski, V. 2000, AJ, 119, 3060
de Koter, A. 1993, Studies of the Variability of LBVs, Ph.D. Univ. Utrecht
Lamers, H. J. G. L. M., Zickgraf, F.-J., de Winter, D., Houziaux, L., & Zorec, J. 1998, A&A, 340, 117

Langer, N., Garcia-Segura, G., & Mac-Low, M. 1998, Reviews in Modern Astronomy, 11, Stars and Galaxies, ed. R. E. Schielicke (Hamburg, Germany: Astronomische Gesellschaft), 57
Leibowitz, E. M. 1977, A&A, 56, 265
Leinert, C., Richichi, A., & Haas, M. 1997, A&A, 318, 472
Likkel, L., Forveille, T., Omont, A., & Morris, M. 1991, A&A, 246, 153
Maeder, A., & Meynet, G. 2004, A&A, 422, 225
Mannings, V. 1995, Ap&SS, 224, 185
Marston, A. P. 1995, AJ, 109, 1839
Massey, P. 1981, ApJ, 246, 153
Meaburn, J., Boumis, J. A., Redman, M. P., López, J. A., & Mavromatakis, F. 2004, A&A, 422, 603
Mendoza, E. E. 1958, ApJ, 128, 207, 123, 1639
Meynet, G., & Maeder, A. 2003, A&A, 404, 975
Miroshnichenko, A. S. 1996, A&A, 312, 941
Miroshnichenko, A. S., & Corporon, P. 1999, A&A, 349, 126
Miroshnichenko, A. S., Fremat, Y., Houziaux, L., et al. 1998, A&AS, 131, 469
Miroshnichenko, A. S., Gray, R. O., Vieira, S. L. A., Kuratov K. S., & Bergner, Y. K. 1999, A&A, 347, 137
Miroshnichenko, A. S., Chentsov, E. L., Klochkova, V. G., et al. 2000, A&AS, 147, 5
Miroshnichenko, A. S., Levato, H., Bjorkman, K. S., et al. 2004, A&A, 417, 731
Miroshnichenko, A. S., Bjorkman, K. S, Grosso, M., et al. 2005, A&A, 436, 653
Monnier, J. D., Berger, J.-P., Milan-Gabet, R., et al. 2006, ApJ, 647, 444
Morris, P. W., Voors, R. H. M., Lamers, H. J. G. L. M., & Eenens, P. R. J. 1997, in Luminous Blue Variables: Massive Stars in Transition, ed. A. Nota, & H. Lamers, ASP Conf. Ser., 120, 20
Muratorio, G., Rossi, C., & Friedjung, M. 2006, A&A, 450, 593
Nota, A., Livio, M., Clampin, M., & Schulte-Ladbeck, R. 1995, ApJ, 448, 788
Oudmaijer, R., & Drew, J. 1999, MNRAS, 305, 160
Owocki, S. P., Cranmer, S. R., & Gayley, K. G. 1996, ApJ, 471, L115
Parthasarathy, M., Vijapurkar, J., & Drilling, J. S. 2000, A&AS, 145, 269
Pereira, C. B., Landaberry, S. J. C., & de Araújo, F. X. 2003, A&A, 402, 693
Pirzkal, N., Spillar, E. J., & Dyck, H. M. 1997, ApJ, 481, 392
Pogodin, M. A., Miroshnichenko, A. S., Tarasov, A. E., et al. 2004, A&A, 417, 715
Rodriguez, L. F., & Bastian, T. S. 1994, ApJ, 428, 324
Schulte-Ladbeck, R. E. 1998, in B[e] stars: Proceedings of the Paris workshop held 9−12 June, 1997, ed. A. M. Hubert, & C. Jaschek (Dordrecht; Boston: Kluwer Academic Publishers), Astrophysics and Space Science library; v. 233, 253
Shevchenko, V. S., Grankin, K. N., Ibragimov, M. A., et al. 1994, in Nature and Evolutionary Status of Herbig Ae/Be Stars, ed. P. S. Thé, M. R. Pérez, & E. P. J. van den Heuvel, ASP Conf. Ser., 62, 55
Simon, T., & Dyck, H. M. 1977, AJ, 82, 725
Smith, N., & Hartigan, P. 2006, ApJ, 638, 1045
Stothers, R. B., & Chin, C.-W. 1996, ApJ, 468, 842
Takami, M., Bailey, J., & Chrysostomou, A. 2003, A&A, 397, 675
Thé, P. S., de Winter, D., & Perez, M. R. 1994, A&AS, 104, 315
Thum, C., Matthews, H. E., Martin-Pintado, J., et al. 1994, A&A, 283, 582
Umana, G., Cerrigone, L., Trigilio, C., & Zappalá, R. A. 2004, A&A, 428, 121
Valenti, J. A., Johns-Krull, C. M., & Linsky, J. L. 2000, ApJS, 129, 399
Vinković, D., & Jurkić, T. 2007, ApJ, 658, 462
Voors, R. H. M. 1999, Ph.D. Thesis, University of Utrecht
Walborn, N. R. 1976, ApJ, 204, L17
Waters, L. B. F. M., Morris, P. W., Voors, R. H. M., & Lamers, H. J. G. L. M. 1997, in Luminous Blue Variables: Massive Stars in Transition, ed. A. Nota, & H. Lamers, ASP Conf. Ser., 120, 326
Weis, K. 2003, A&A, 408, 205
Wolf, B., & Stahl, O. 1985, A&A, 148, 412
Zickgraf, F.-J. 1992, in Nonisotropic and Variable Outflows from Stars, ed. L. Drissen, C. Leitherer, & A. Nota, ASP Conf. Ser., 22, 75
Zickgraf, F.-J. 2003, A&A, 408, 257
Zickgraf, F.-J., & Stahl, O. 1989, A&A, 223, 165
Zickgraf, F.-J., Wolf, B., Stahl, O., Leitherer, C., & Klare, G. 1985, A&A, 143, 421
Zijlstra, A., Pottasch, S., & Bignell, C. 1990, A&AS, 82, 273
Zorec, J. 1998, B[e] stars: Proceedings of the Paris workshop held 9−12 June, 1997, ed. A. M. Hubert, & C. Jaschek, Astrophysics and Space Science Library, 233, 27